

LHC results and prospects: Beyond Standard Model

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Abstract

We present the results and prospects for searches beyond the Standard Model (SM) at the LHC by the ATLAS and CMS collaborations. The minimal supersymmetric extension of the SM has been investigated in various configurations and lower limits are set on the s-particle masses. The searches for other scenarios of physics beyond the SM are also presented and lower limits on the mass scale are derived in a large variety of models (new heavy gauge bosons, extra-dimensions, compositeness or dark matter). The prospects for physics using 300 /fb and 3000 /fb of data at the high luminosity LHC are also shown.

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1 Introduction

The LHC extended the searches for physics beyond the Standard Model (SM) in an unprecedented way. The integrated luminosity recorded in 2011 and 2012 reached 5 /fb and 21 /fb for both the ATLAS and CMS experiments, for the corresponding center-of-mass energies of 7 TeV and 8 TeV. The searches for new physics are oriented to the minimal supersymmetric extension of SM, as well as any theoretical scenario including new heavy gauge bosons, extra-dimensions, compositeness and dark matter, or any other signs of new physics beyond the SM.

2 Data taking and experiments

2.1 Data taking at the LHC

The years 2011 and 2012 have been extremely successful for the LHC machine. The luminosity reached the record of $7.6 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ at the end of the pp operations. The delivered integrated luminosity was greater than 6 /fb in 2011 and greater than 23 /fb in 2012 for both the ATLAS and CMS detectors. The data taking efficiency was better than 90% and the recorded integrated luminosity was of the order of 5 /fb and 21 /fb respectively in 2011 and 2012 for both experiments [1][2], as shown in Fig.1.

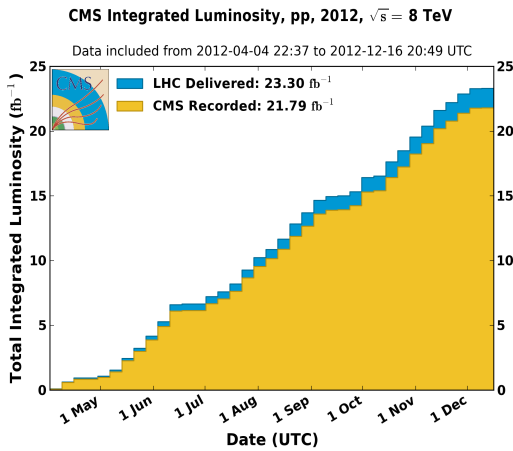


Figure 1: Delivered (blue) and recorded (orange) integrated luminosity during the 2012 data taking in CMS [1].

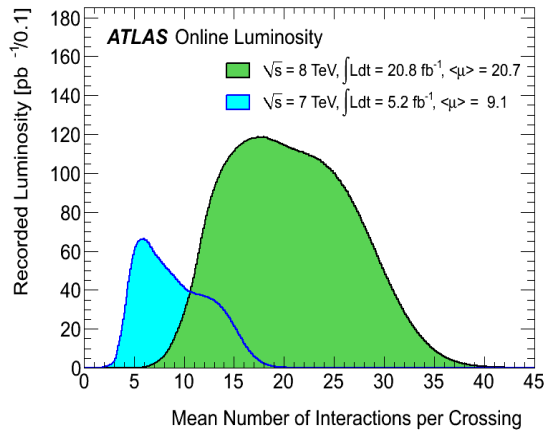


Figure 2: Mean number of interactions per crossing in ATLAS in 2011 (blue) and 2012 (green) [2].

The energy per beam was 3.5 TeV in 2011 and was increased to 4 TeV in 2012. After the first long shutdown on-going up to the beginning of 2015, an intermediate phase of data taking with beams of 6.5 TeV will occur and afterwards the LHC beams will reach their nominal energy of 7 TeV. Then the full center-of-mass energy of 14 TeV will be used to look for new physics.

The mean number of interactions per crossing increased with the luminosity. During the 8 TeV operations, this number was on average 20 and even reached the value of 40 at the end of the pp operations in 2012, as shown in Fig.2. The pile-up is indeed a key parameter in the physics analyses and will reach the value of 140 at the end of the High-Luminosity (HL)-LHC program.

2.2 ATLAS and CMS detectors

ATLAS [3] and CMS [4] are multi purpose detectors using a large variety of technologies in order to identify and trigger on electrons, photons, muons, jets and missing transverse energy objects [5][6]. Both experiments have pixel and tracker detectors made of semiconductors. ATLAS is using a liquid Ar electromagnetic calorimeter while CMS has chosen a PbWO₄ crystal technology. The hadronic calorimeter of ATLAS uses liquid Ar in the endcaps and tiles in the barrel. The CMS hadronic calorimeter is a mixture of brass and scintillating material. Both experiments are equipped with similar muon detectors (drift tubes, cathode strips chambers and resistive plate chambers), but the geometry of the magnetic field (pure solenoid in CMS, internal solenoid plus toroidal in ATLAS) demands a different localization of these three kinds of detectors.

3 SUSY searches

Several arguments exist in favour of a supersymmetric (SUSY) extension of the SM. The hierarchy problem can be solved without too much fine-tuning and then the SUSY theory demands relatively light stop quarks (below 1 TeV). The implication of the discovery of the scalar boson at 126 GeV is that one stop quark can be light but the other stop should be heavier; but this is not yet in contradiction with the previous argument. The gauge coupling unification at the Grand Unified Theories (GUT) scale cannot occur in the SM, but it could occur in the SUSY extension for certain set of parameters. If R-parity is conserved ($-1^{(3(B-L)+2S)} = +1/-1$ respectively for SM/SUSY particles), a natural dark matter candidate is provided being the neutralino1, as the Lightest Supersymmetric Particle (LSP) will be stable. Finally a link to gravity is given in the SUSY theory, which is not the case in the SM.

3.1 SUSY processes

The different SUSY production processes can be sorted in several categories: gluino, squark and electroweakino (ie. chargino/neutralino/slepton) productions. Fig.3 shows the different cases and the corresponding expected cross sections [7]. These SUSY cross sections are lower by orders of magnitude than the SM processes. The SM background determination will be achieved using both MC simulation as well as some data driven methods.

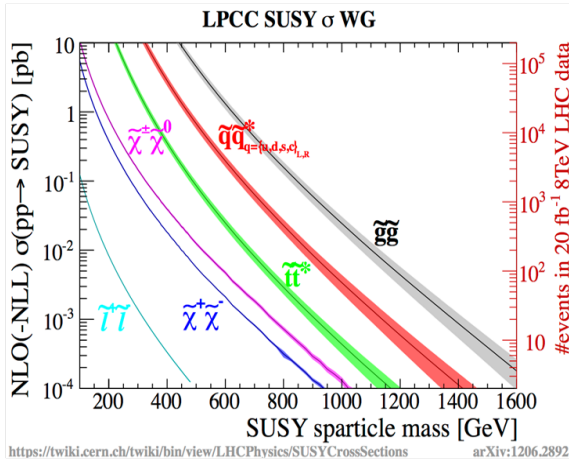


Figure 3: Predicted SUSY cross sections at 8 TeV [7].

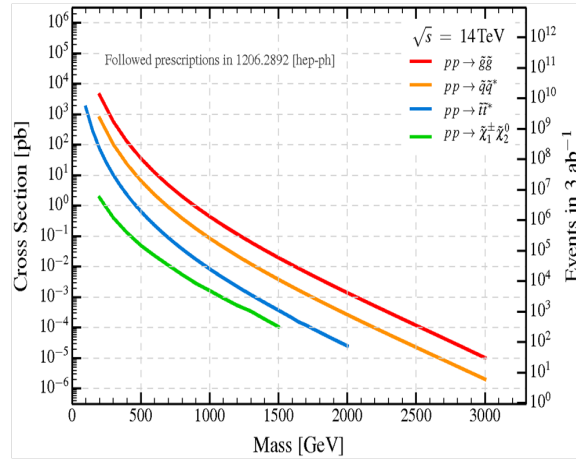


Figure 4: Predicted SUSY cross sections at 14 TeV [8].

3.2 Framework for interpretation

Several frameworks are commonly used to interpret the results of the SUSY searches. In order to reduce the number of parameters in the Minimal Supersymmetric Standard Model (MSSM), which contains originally 105 parameters, some constraints are introduced. The mSUGRA model for instance is a 5 parameter model assuming the unification of sfermion masses, gaugino masses and tri-linear couplings at the GUT scale. But there are also other SUSY models, like GMSB (Gauge Mediated Symmetry Breaking) or pMSSM (phenomenological MSSM) using different constraints. Another approach is to consider only the dominant SUSY cascades and to assume the branching ratio to 100%. They are called Simplified Model Spectra (SMS). The topology is described by masses and cross sections. It allows to perform wider searches than the constrained models.

3.3 Results and prospects in SMS

Assuming the R-parity to be conserved, Fig.5 shows the exclusion limit obtained using the gluino production and combining several channels (from zero to three leptons) in the CMS experiment [9]. Fig.6 shows an example of a schematic diagram of a dominant SUSY cascade (gluino production, the gluino decaying to a top pair and a neutralino), without showing the intermediate particles. The gluino mass had been probed up to 1.3 TeV. The limit is given at 95% confidence level (CL), using all 7 TeV and 8 TeV data.

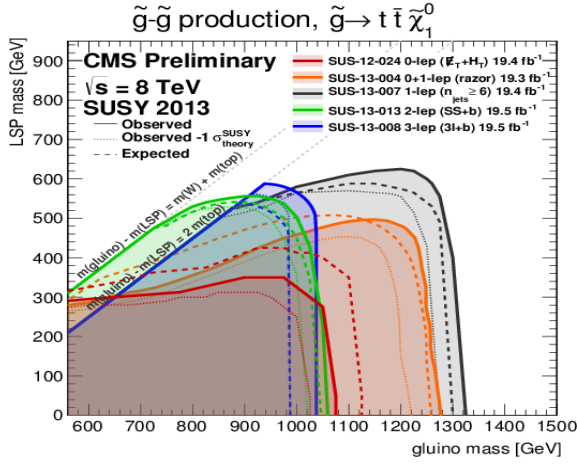


Figure 5: Gluino mass limit area from CMS using all 7 TeV and 8 TeV data [9].

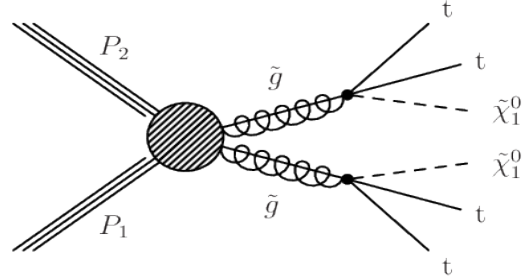


Figure 6: SUSY dominant cascade in T1 region (gluino production) in SMS model [9].

Fig.7 shows the exclusion area for the stop production in ATLAS assuming the R-parity to be conserved [10]. Two different regions are shown depending on the final state (stops decaying to top and LSP on the left ; stops decaying to W, b quark and LSP on the right). The stop mass is probed up to roughly 700 GeV. The previous limit from the CDF experiment is also superimposed, showing the improvement by the LHC.

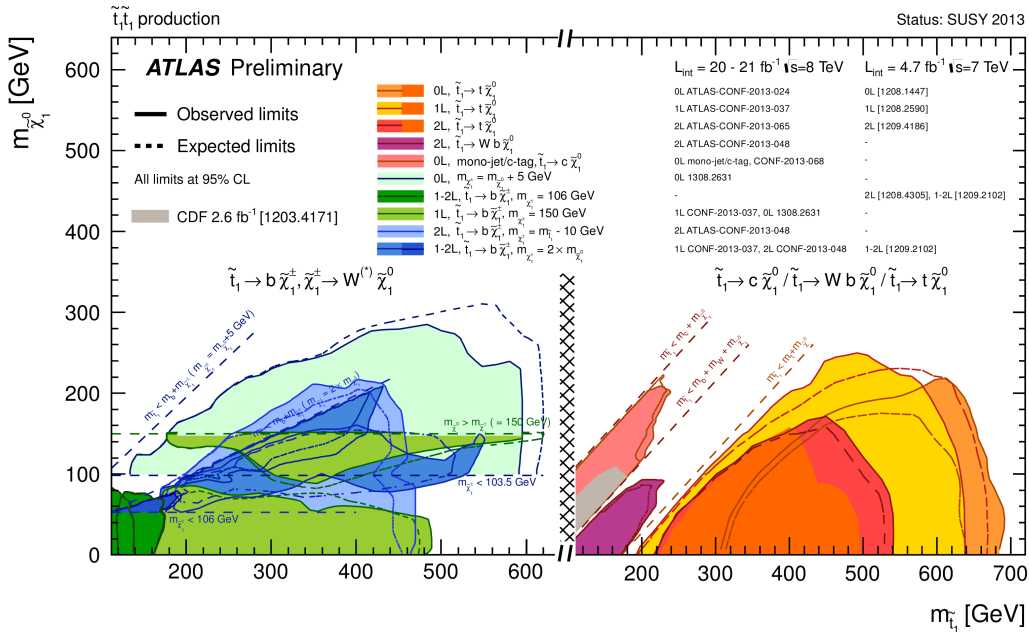


Figure 7: Stops mass limits in ATLAS using all 7 TeV and 8 TeV data [10].

The electroweakino production (ie. chargino, neutralino or slepton) in the R-parity conserved scenario gives the advantage of a clean signature, up to four leptons and high missing transverse energy. Fig.8 summarises the different limits obtained in CMS, depending on the decay chain via a slepton or a W/Z boson [11].

R-parity can be also violated (RPV). If only one among the leptonic and baryonic violating terms in the lagrangian is non-zero, then there is no problem with the proton decay. In this case, the missing transverse energy due to the LSP is suppressed. The final state will encompass several jets, including b-jets and leptons. In this RPV configuration, the stop mass is probed up to 1.0 TeV, the gluino mass up to 1.5 TeV and the squark mass up to 1.7 TeV using the 8 TeV data in ATLAS [12] and CMS [13].

The prospects for SUSY searches have been performed with both assumptions of 300 /fb (presumably obtained

around 2022) and 3000 /fb (high luminosity LHC program, around 2030). The center-of-mass energy in this case is 14 TeV. The SUSY cross sections will benefit from this improvement as shown on Fig.4. Fig.9 shows the ATLAS expected exclusion limit in the gluino-squark masses plane, as well as the discovery reach for both targeted integrated luminosities. The expected sensitivity area will be largely extended [14].

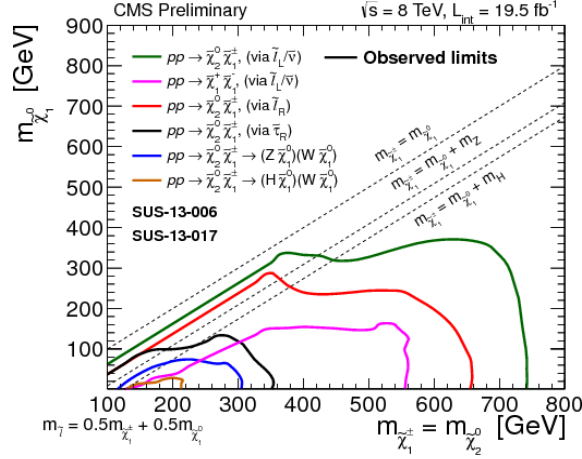


Figure 8: Electroweakino limits obtained in CMS using all 7 TeV and 8 TeV data [11].

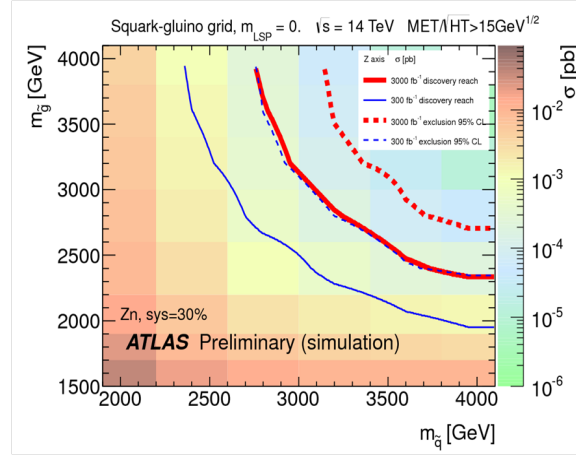


Figure 9: Expected gluino mass limit using 300 /fb and 3000 /fb at 14 TeV in ATLAS [14].

4 Other searches beyond the SM

The other searches for physics beyond the SM, also called Exotica program, are covering a wide range of analyses looking for additional heavy gauge bosons (W' , Z'), extra-dimensions, compositeness, dark matter, also microscopic black holes, or any other scenario outside the SM (hidden valleys, unparticles ...). The typical topologies in Exotica imply some high transverse momentum objects (electron, muon) at the TeV scale, high mass dilepton, diphoton or dijet resonances, or multi-lepton anomalous production.

4.1 High transverse momentum leptons

Several analyses in Exotica are based on high transverse momentum lepton searches. For instance the heavy gauge boson W' mass is probed up to 3.3 TeV in CMS in the sequential SM, assuming the same branching ratio as in the SM. Fig.10 shows the results combining both electron and muon channels [15].

The searches for excited electrons or muons are also using high transverse momentum leptons. These excited states could be the consequence of fermion substructure (compositeness). The typical decays in this analysis would be a lepton and a gauge boson or a lepton and a pair of fermions. The probe of the mass scale of excited leptons is up to 2.2 TeV in ATLAS [16]. Fig.11 shows the searches in ATLAS using the 8 TeV data and the comparison with previous results at 7 TeV in ATLAS and CMS.

4.2 High mass resonances

Fig.12 and Fig.13 show two high mass resonance distributions, respectively the di-electron and the dijet spectrum. The sum of the SM backgrounds and the data are in good agreement, as shown also on the ratio plot below each distribution. Then a limit can be derived for several Exotica models.

The di-lepton (electron or muon) resonances allow first of all to put a limit on the Z' boson mass. The sequential SM (same coupling to fermions as the Z boson) being used as benchmark, the lower mass limit obtained in ATLAS is 2.9 TeV [17]. The extra-dimensions are probed by using the di-lepton and di-photon final states as shown on Fig.14. Depending on the number of extra-dimensions, the mass scale has been probed up to 3 TeV for most of the scenarios [18]. Fig.15 shows the different limits obtained from the dijet mass spectrum interpretation in the following models: strings, excited quarks, axigluon/colorons, W' , Z' and also Randall-Sundrum gravitons. The lower mass limit reached in CMS is up to 5.1 TeV [19].

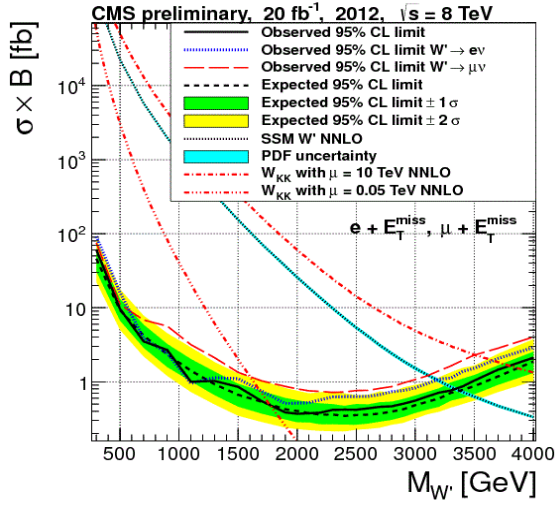


Figure 10: W' searches in CMS in the electron and muon channels using the 8 TeV data [15].

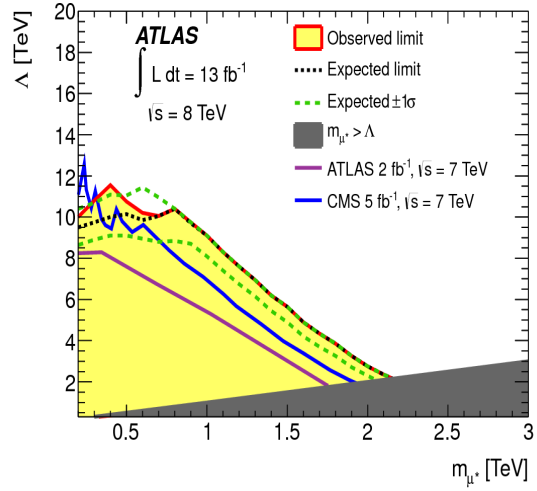


Figure 11: Excited lepton searches in ATLAS using the 8 TeV data [16].

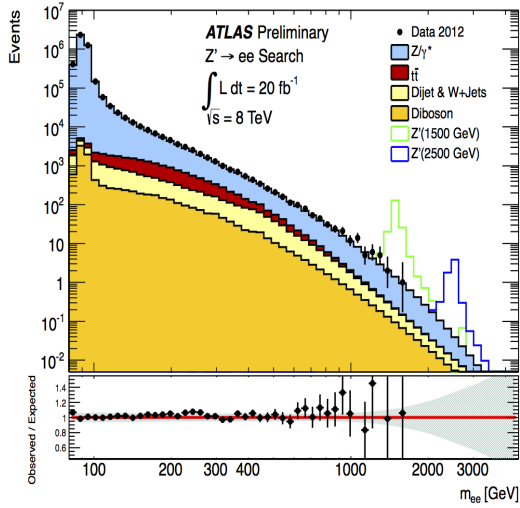


Figure 12: Di-electron mass spectrum in ATLAS using the 8 TeV data [17].

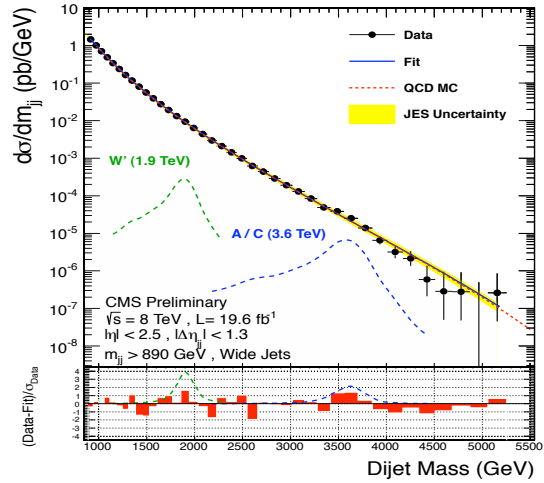


Figure 13: Dijet mass spectrum in CMS using the 8 TeV data [19].

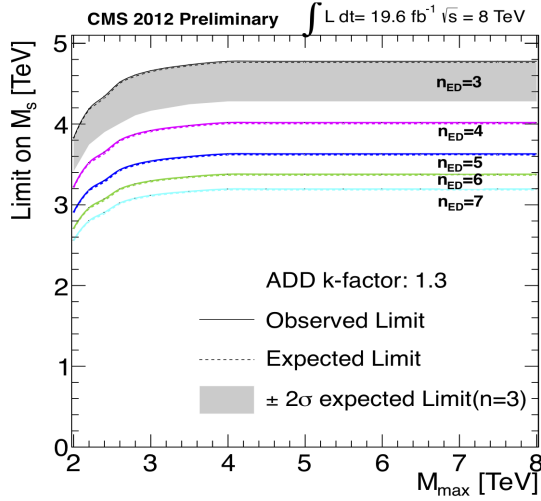


Figure 14: Lower limit from CMS on the model parameter M_S in an extra spatial dimension model using the 8 TeV data, depending on the number n_{ED} of extra dimensions [18].

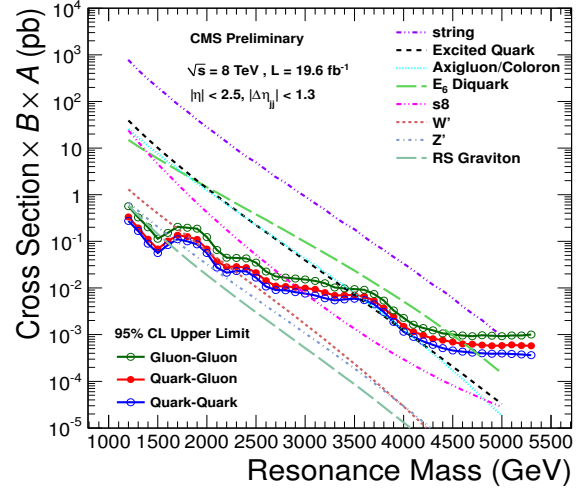


Figure 15: Search for narrow resonances using the di-jet mass spectrum at 8 TeV in CMS [19].

4.3 Anomalous lepton and top production

Several inclusive model independent analyses are based on searches for anomalous multi lepton production. Excited neutrino, fourth-generation quark or doubly-charged Higgs boson models are predicting anomalous multiple (at least three) lepton production. The scalar sum of the transverse momentum of the three charged leading leptons is compared to the SM expectation and an upper limit on the event yields due to non-SM processes is derived [20]. Fig.16 is summarizing these searches in ATLAS.

The Kaluza-Klein (KK) excitations of gluons or gravitons in the extra-dimensions models, as well as new heavy gauge boson could have enhanced couplings to top anti-top pairs. Generic searches for anomalous production in the top/anti-top invariant mass spectrum allowed to put some new lower limits on the Z' mass (2.1 TeV) and also on the Randall-Sundrum KK gluons (2.5 TeV) using the 8 TeV data in CMS [21]. Fig.17 shows the upper limit on the Z' cross section obtained in CMS, taking into account the branching ratio of the Z' into top/anti-top pairs.

4.4 Dark matter searches

The dark matter-nucleon scattering cross section can be constrained in both spin dependent or independent interaction models [22]. The collider experiments are sensitive in particular to the low mass region below 10 GeV. Fig.18 and Fig.19 show the ATLAS searches for dark matter, as well as the comparison with the direct detection experiments (XENON100, CoGeNT, CDMS, COUP ...). This analysis is based on the assumption of Weakly Interacting Massive Particle (WIMP) pair production via an unknown intermediate state and an initial radiation of a W or Z boson. The results can be also interpreted to set an upper limit on the cross section of the Higgs boson decaying into invisible particles.

5 Conclusion

So far no hints of new physics beyond the SM have been found at the LHC. The SUSY searches in both ATLAS and CMS allow to probe the gluino mass up to around 1.3 TeV while the squark masses are probed up to roughly 700 GeV. SUSY models with R-parity violated have been also investigated. The exotica program has not shown any excess and limits are set on the mass scale for a lot of scenarios. The inclusive model independent analyses permit to widen the range of searches, without any bias on the expected signal. Both SUSY and Exotica searches will benefit from the higher center-of-mass energy and the increased luminosity in the next years and afterwards, using the HL-LHC program.

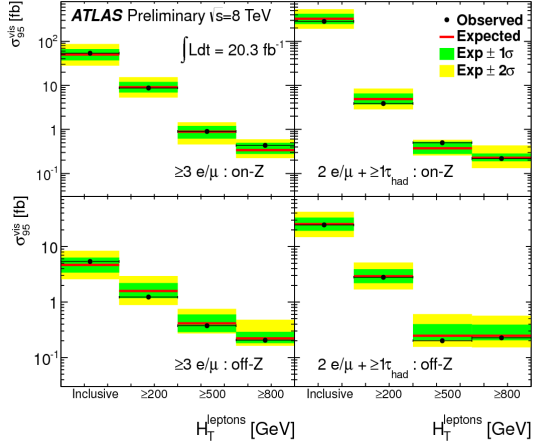


Figure 16: Limit on the visible cross sections for several signal channels as a function of the lower bounds on the scalar sum of the transverse momentum of the leptons [20].

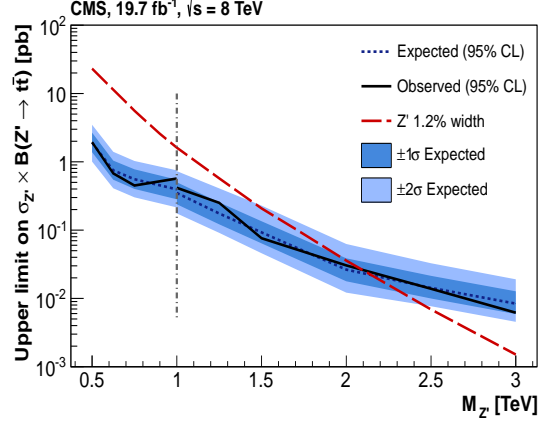


Figure 17: Limits on the production cross section times branching fraction for a Z' using the top anti-top mass spectrum at 8 TeV in CMS [21].

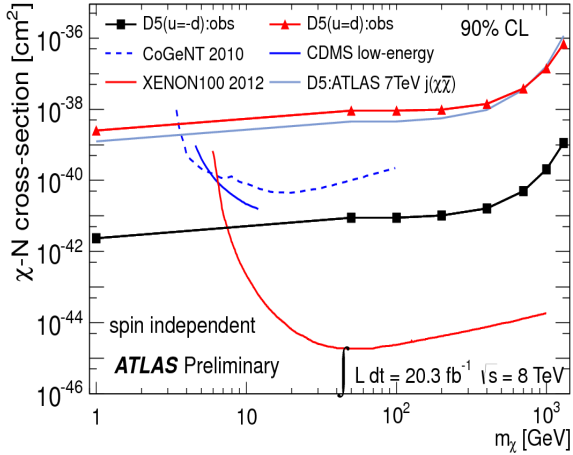


Figure 18: Dark matter searches in spin independent model in ATLAS using 8 TeV data [22].

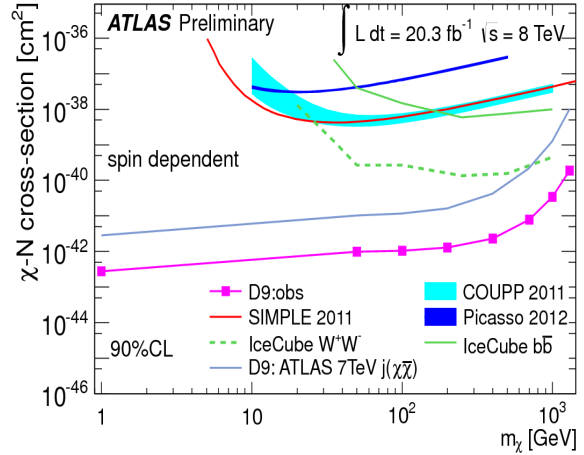


Figure 19: Dark matter searches in spin dependent model in ATLAS using 8 TeV data [22].

Acknowledgments

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